CIB-W18/37-15-7

**INTERNATIONAL COUNCIL FOR RESEARCH AND INNOVATION
IN BUILDING AND CONSTRUCTION**

WORKING COMMISSION W18 - TIMBER STRUCTURES

ACCEPTANCE CRITERIA FOR THE USE OF STRUCTURAL INSULATED PANELS IN HIGH RISK SEISMIC AREAS

B Yeh

T D Skaggs

T G Williamson

Z A Martin

APA - The Engineered Wood Association

UNITED STATES

MEETING THIRTY-SEVEN
EDINBURGH
UNITED KINGDOM
AUGUST 2004

Acceptance Criteria for the Use of Structural Insulated Panels in High Risk Seismic Areas

Borjen Yeh, Ph.D., P.E.
Thomas D. Skaggs, Ph.D., P.E.,
Thomas G. Williamson, P.E.
Zeno A. Martin, P.E.
APA - The Engineered Wood Association, U.S.A.

Abstract

One of the fastest growing segments of the US housing construction industry is the use of structural insulated panels or SIPs. These components are also used extensively in commercial construction in the US and other countries. Emphasizing the growing importance of SIPs worldwide is a recent work item initiated by ISO TC 165 in the development of an international standard for the design of SIPs. In the US, SIPs are typically constructed using a foam core with outside layers of oriented strand board (OSB). While it would seem logical that a structural component having double "skins" of OSB would perform well when subjected to high lateral forces, such as those experienced during an earthquake, the US building codes have limited the use of SIPs to low to moderate seismic zones. This limitation is due to the concern that the sealants used in the manufacturing and installation of SIPs may affect their seismic performance.

Since the US building codes do not explicitly cover SIPs, building officials have the authority to accept their use under code-compliance evaluation reports, which are typically published by the ICC Evaluation Service (ICC-ES). These code reports are based on analysis of test data in accordance with ICC-ES AC04, *Acceptance Criteria for Sandwich Panels*. This paper describes efforts by APA - The Engineered Wood Association and the Structural Insulated Panel Association (SIPA) to revise AC04 in gaining recognition for the use of SIPs in high seismic risk zones. APA conducted a series of cyclic load tests using conventional wood framed shear walls and SIP walls. Results of this study confirmed that the SIP walls had equal or better performance than the conventionally framed walls. An analytical procedure for cyclic SIP shearwall tests was developed by APA and was approved by ICC-ES in the revised AC04, which now permits the use of SIPs in high seismic risk zones. To achieve this acceptance, a SIP manufacturer will be required to conduct the aforementioned tests in accordance with the new provisions of AC04.

1. Introduction

Structural Insulated Panels (SIPs) have had a long history of successful performance. The Forest Products Laboratory in Madison, Wisconsin, assembled the first demonstration house using "stress-skin panels" in 1937. Since then, SIPs have illustrated exemplarily structural performance in many parts of the world, including high wind and high seismic risk areas. In fact, it has been reported that SIP structures withstood the 1995 Kobe Japan earthquake (magnitude 7.2) with minimal damage (www.pbspanels.com). In 2003, approximately one percent of the nearly two million housing starts were with SIPs in the US. Although this if a relatively small percentage of the overall market share, it is important to note that the SIPs market share has nearly doubled since 1997 (APA, 2004). In addition, the Structural Insulated Panel Association (SIPA) in the US is launching a five-year plan to double this again in the next 5 years. The attractive attributes of SIPs have made them popular in areas of the US where stringent energy codes or severe weather fluctuations are coincidental with high seismic risk.

The International Building Code, IBC, (ICC, 2003) has highlighted an issue that affects manufacturers of SIPs in particularly the following section:

> ***2305.3.9 Adhesives.*** *Adhesive attachment of shear wall sheathing is not permitted as a substitute for mechanical fasteners, and shall not be used in shear wall strength calculations alone, or in combination with mechanical fasteners in Seismic Design Category D, E and F.*

Since the US building codes do not explicitly cover SIPs, building officials have the authority to accept their use under code-compliance reports, which are typically published by the ICC Evaluation Service (ICC-ES). These reports are based on analysis of test data in accordance with ICC-ES AC04, *Acceptance Criteria for Sandwich Panels*. As expected, the use of SIPs is limited to Seismic Design Categories A, B and C only in accordance with the IBC.

A brief history should be given to the "adhesive ban". The IBC used the NEHRP Provisions (FEMA, 2001a) as a "resource document". The Building Seismic Safety Council (BSSC) Technical Subcommittee 7 deliberated on the "adhesive ban" before it was adopted into the NEHRP Provisions based on the consideration that "the current ban on adhesive was imposed for high seismic because of the increased stiffness and associated attracted loads" (BSSC, 2000). However, the restriction was originally based on observations of light framed walls with rigid adhesives between the sheathing and the wood studs. The testing, conducted with rigid construction adhesive, led to impressive increases in wall stiffness and ultimate loads, but failed in a non-ductile mode.

There are two types of "adhesives" that are typically used in SIP assemblies. The first is the adhesive between the oriented strand board (OSB) skins (typical) and the expanded polystyrene core. The second type of "adhesive" is the sealant that is used to prevent air infiltration. The sealants are typically applied to all wood-to-wood connections and wood-to-foam connections. Sealants, depending on their chemical formulation, can provide rigid bonds. After sealants are applied, the SIPs are assembled similar to other light frame wood construction. The panels are typically connected with power driven fasteners into wood top and bottom plates and wood splines.

In order to address the use limitation of SIPs in high seismic risk zones, an analytical procedure for cyclic SIP shearwall tests was developed by APA in 2003 to demonstrate, via cyclic shear wall testing, that SIPs perform similarly to light framed wood walls with wood structural panels. The significance of demonstrating equivalence is light framed wood walls with wood structural panels are code-recognized systems that have historically shown adequate performance in seismic events.

2. Justification for Using Cyclic Testing to Show Equivalence

The 2003 IBC lists seismic design coefficients and factors for approximately 80 different seismic force-resisting systems in Table 1617.6.2. These listed systems range from steel eccentrically braced frames to ordinary plain concrete shear walls. Ranging between these two extremes in terms of seismic performance are light framed wood structural panels shear walls. By code definition, wood structural panels include plywood and OSB. For seismic design following the US building code, there are three listed attributes that are of importance (see Figure 1 for graphical representation of the three attributes):

1. Response modification coefficient, R,
2. System over-strength factor, Ω_o,
3. Deflection amplification factor, C_d

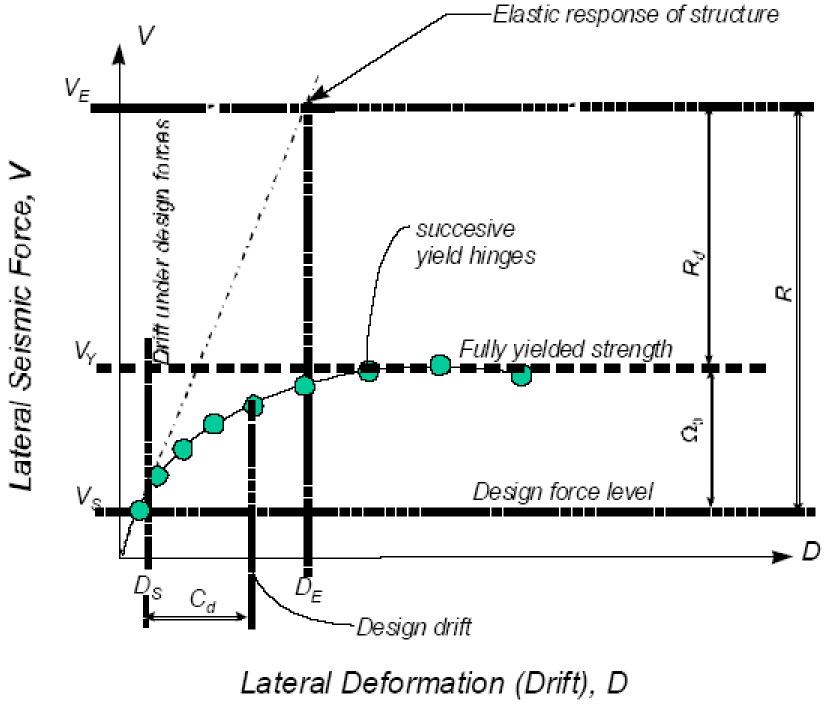

Figure 1. Inelastic force-deformation curve (Originally published as Figure C5.2-1, FEMA, 2001b)

The response modification coefficient, in practice, is the most used factor of the three aforementioned attributes. The response modification coefficient "represents the ratio of the forces that would develop under the specified ground motion if the structure had an entirely linearly elastic response" (FEMA, 2001b). The coefficient, which is always greater than 1.0, is applied to the load side of the equation and effectively reduce the design base shear. This reduction is due to 1.) as the structure begins to perform inelastically, the effective period of the structure is lengthened, which for many structures results in reducing strength demand, and 2.) inelastic behaviour results in a significant amount of energy dissipation (through hysteretic damping). These two combined effects explain the satisfactory performance of structures that should, on paper, have not performed well in a seismic event. The listed values (ICC, 2003) of the response modification coefficient range from 1.5 (one example is ordinary plain masonry shear walls) to 8 (one example is an eccentrically braced steel frame). For light framed walls with wood structural panels, the response modification coefficient is equal to 6.5. It should be noted that the determination of the response modification coefficient is based on committee decisions; thus, there is no analytical method available currently for deriving the response modification coefficient for an unlisted system in the IBC.

The over-strength factor is used for determining the maximum seismic load effect and represents the ratio of the fully yielded strength of the system to the design strength of the system (See Figure 1). It is also related to the response modification coefficient and the ductility factor. In practice, this value is also based on committee decisions and ranges from 2 to 3 (ICC, 2003). As similar to the response modification coefficient, cyclic test data is typically not used to establish the over-strength factor. For light frame walls with wood structural panels, the over-strength factor is established as 3.0 (ICC, 2003). The IBC effectively requires that a strength level calculation be performed for lateral force resistance systems that could lead to non-ductile failures. The intended purpose of this code provision is to assure that the force demand is delivered to the ductile elements. Examples are the design of shear wall collectors and the design of support for discontinuities in the vertical system (i.e. unstacked shear walls). Note that the IBC exempts some light frame structures for these requirements based on their long history of successful performance when subjected to seismic forces.

The well-recognized definition of the deflection amplification factor is the ratio of anticipated inelastic drift to the elastic deformation calculated under the reduced design forces. The deflection amplification factor takes into account the brittleness of the system. The range of listed deflection amplification factors (ICC, 2003) is 1¼ - 5. For light framed wood walls with wood structural panels, the deflection amplification factor is equal to 4. As with the response modification coefficient and the over-strength factor, test data is typically not used to confirm the deflection amplification factor. In practice, the elastic lateral force resistant system deformation is determined by using empirical shear wall deflection equations. These elastic deflection are then "amplified" by the deflection amplification factor and checked against the allowable story drift, which is prescribed as 2.5 percent wall height for most light framed shear walls (Table 1617.3.1, ICC, 2003).

For systems that are not listed under Table 1617.6.2, the following clause is provided in the 2003 IBC (ICC):

> ***1617.6.2 Seismic-force-resisting systems.*** *… For seismic-force-resisting systems not listed in Table 1617.6.2, analytical and test data shall be submitted that establish the dynamic characteristics and demonstrate the lateral-force resistance and energy dissipation capacity to be equivalent to the structural systems listed in Table 1617.6.2 for equivalent response modification coefficient, R, system over-strength coefficient,* Ω_o*, and deflection amplification factor,* C_d*, values …*

Therefore, the purpose of the evaluation procedure listed in section 3 of this paper is to meet the intent of Section 1617.6.2 of the IBC (ICC, 2003). In the past 10 years in the US, there has been an unprecedented amount of cyclic testing of wood shear wall systems. However, there has been little consensus on how these data should be analyzed. The purpose of the evaluation procedure is to compare the dynamic characteristics of a system

(SIPs) that is not listed in the code with a code listed seismic force resisting system (light framed wood walls sheathed with wood structural panels). If the test data demonstrated similar performance characteristics, then one could infer that similar in-service seismic performance would be realized. If this is the case, the limitations of the two systems as well as the seismic design coefficients should be similar.

3. Evaluation Procedure

The evaluation procedure outlined below is based on Appendix A of AC04 (ICC-ES, 2004), which was originally proposed by APA staff to the ICC-ES Evaluation Committee. As previously discussed, the purpose of this evaluation procedure is to permit the use of SIPs in higher seismic design categories. The evaluation procedure, as stated in Appendix A of AC04 "is not intended to determine design capacities, the response modification coefficient, R, the system over-strength factor, Ω_o, or the deflection amplification factor, C_d". The purpose of this evaluation procedure is to show that SIP assemblies, with or without sealants, perform similarly to light-frame walls with wood structural panels.

The essence of conducting the comparison tests is to test matched walls as a benchmark. Although completely matching SIP assemblies and conventional light framed wall assemblies is not possible, the matched tests are intended to duplicate as many of the factors as possible. For example, SIPs are typically manufactured with an expanded polystyrene core sandwiched between two sheets of wood structural panels. The matched light frame walls for this test program were sheathed with wood structural panels on both sides of the frame. The same type and number of perimeter fasteners are used to attach the SIP panels into a SIP assembly. The assembly is 2.4m x 2.4m, which is made using two SIP panels or four wood structural panels. Identical tie-down devices are used for both the control (conventional light framed walls) and the SIP assemblies.

3.1 Cyclic Testing

The matched wall tests are conducted following the SEAOSC (1997) test protocol (also known as sequential phase displacement, SPD). If the data is within 15 percent of each other, the results can be combined and the decision point is based on the mean performance. Otherwise, the lowest test value is used. A minimum of three replications is required for each series of tests. In the case of significant variation of test results, the replications can be increased to five, and the decision point may be based on the mean, regardless of variation.

3.2 Data Normalization

Given that the SIP assemblies and the control assemblies may have different design values, the data is normalized by the allowable stress design value. The reason for the different design values is that the SIP systems can have a fundamentally different attachment mechanism than the control assemblies. For example, it is common for individual SIP assemblies to be joined together with a thin (11 mm) wood structural panel spline on each face of the panel.

3.3 Backbone Curve Analysis

The represented backbone curve is the average of the positive and negative cycles of the individual backbone curves. The backbone curve, by definition, is the locus of extremities of the load-displacement hysteresis loops. It represents the peak load from the first cycle of each phase of the cyclic loading. Figure 2 illustrates a hysteresis curve for a conventional light framed wall with the backbone curve overlaid. Figure 3 illustrates a normalized backbone curve (with positive and negative cycles averaged) for three different assemblies. This curve will be further discussed in Section 3.3.4 of this paper.

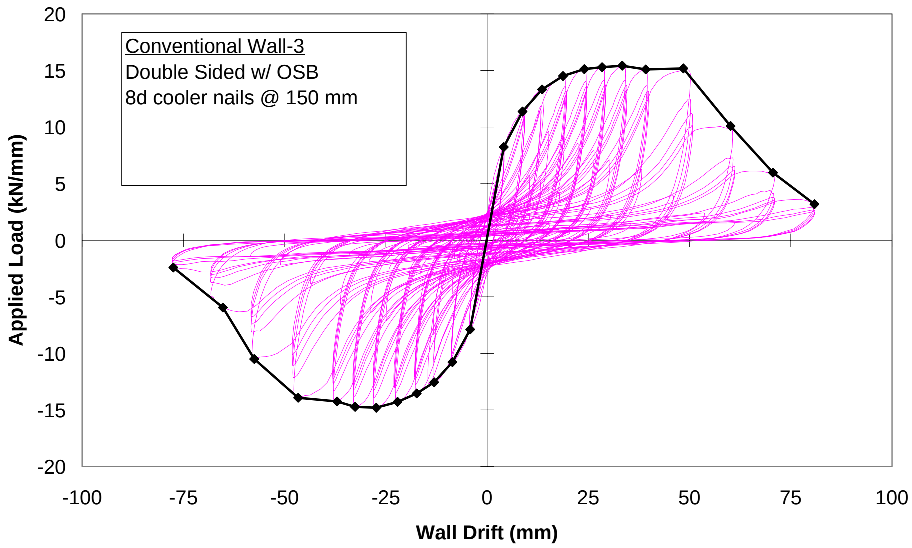

Figure 2. Hysteresis plot of conventional wall (2.4-m wall height) with outer backbone curve overlaid

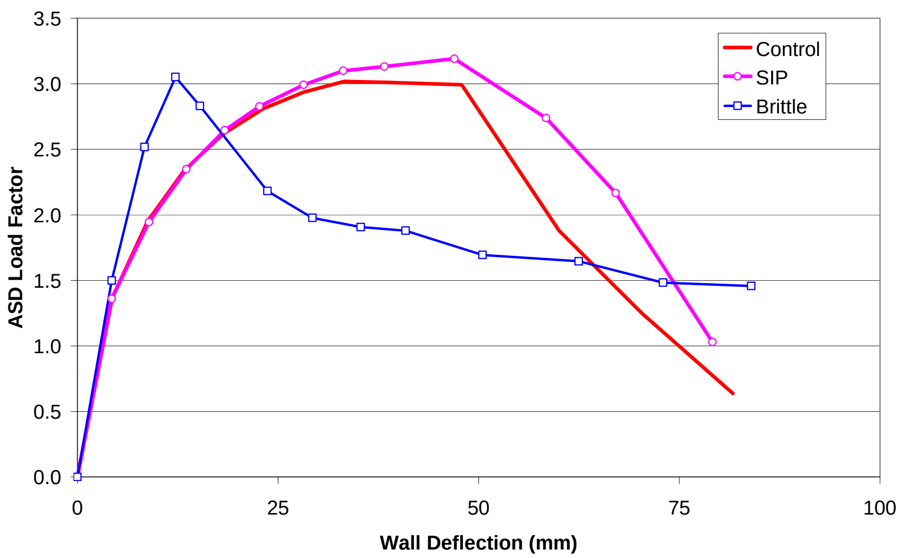

Figure 3. Normalized backbone curves for three different 2.4-m tall assemblies

3.3.1 Ultimate Load Criteria

The normalized ultimate load of the SIP assemblies shall not be less than 90 percent of that for the matched light-framed walls. The importance of the ultimate load is such that a relatively tighter tolerance is required for the ultimate load. In theory, the design value of the assemblies should be based on the ultimate load reduced by a load factor.

3.3.2 Stiffness Criteria

The normalized stiffness, slope of the normalized load versus deflection relationship at normalized load equal to 1.0, for the SIP assemblies shall not be less than 85 percent of that for the matched light-framed walls. Given the authors experience with deflection of wall assemblies as well as the fact that excessive deflection is generally not a life-safety concern, a slightly looser tolerance was specified for stiffness at the allowable stress level.

3.3.3 Deflection at Allowable Story Drift Criteria

The normalized load at the maximum allowable story drift per IBC (2.5 percent wall height, ICC, 2003) for the SIP assemblies shall not be less than 85 percent of that for the matched light-framed walls. As with the stiffness criteria, experience based on extensive assembly testing would indicate that deflection at the allowable story drift could have a large amount of variability. Thus, the tolerance for equivalence was less than the ultimate load criteria.

3.3.4 Application of Backbone Curve Analysis

Figure 3 provides a graphic representation of three backbone curves, including a backbone curve representing the control, a SIP system, and a “Brittle” system. The “Brittle” system was identified before the cyclic testing with expectation that it would fail in a brittle fashion, have little strength after peak load, and fail at a relatively small wall drift. This system was included to demonstrate how the evaluation procedure would identify systems that have significantly different seismic behaviour than light framed walls sheathed with wood structural panels. In terms of the ultimate load criterion, both the SIP assembly and the Brittle assembly exceed the normalized ultimate load of the control. For all practical purposes, the stiffness values at the load factor of 1.0, which represents the stiffness at the allowable stress design value, are identical for all three systems featured in Figure 3. Finally, the normalized load at the allowable story drift of 61 mm is examined. For the SIP assembly, the load at 61 mm exceeds that of the control. For the Brittle system, the load is close to the 85 percent tolerance. However, a closer examination of the backbone curve data is warranted.

3.4 Cumulative Energy Criteria

The area bounded by the normalized hysteresis loops is computed for each cycle of the test protocol. The normalized cumulative energy dissipated by the SIP assemblies shall not be less than 85 percent of that for the normalized matched light-framed walls. Since the current design procedure based on the US building codes does not directly cover cumulative dissipated energy, a looser tolerance than the ultimate load was chosen. Figure 4 demonstrates the application of this criterion for two systems plus the control. Although the SIP system shows a slightly lower normalized cumulative energy for cycles 15 through approximately 58, the normalized cumulative energy is within 85 percent of the control. As a result, the SIP system is acceptable in terms of cumulative energy dissipated. However, as shown in Figure 4, the Brittle system does not meet the normalized cumulative energy dissipation criterion, which demonstrates the effectiveness of these evaluation procedures for identifying systems that fail in a catastrophic fashion.

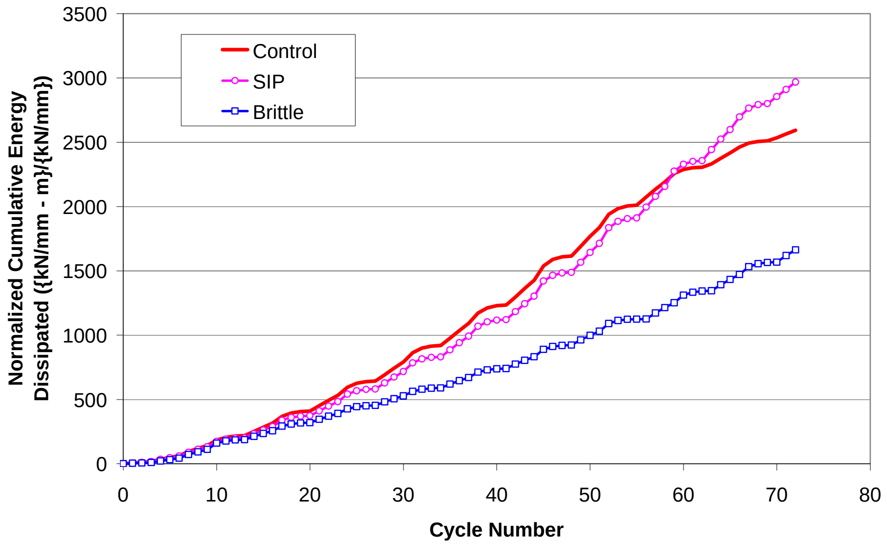

Figure 4. Normalized cumulative energy curves for three different assemblies

3.5 Potential Limitations of Evaluation Procedure

The evaluation methodology adequately identifies equivalent systems in terms of response modification coefficient, which is arguably the most important factor of the published seismic design coefficients. However, it is likely that the proposed criteria will be modified to address the over-strength factor and deflection amplification factor in the future. Figure 5 demonstrates a SIP system (labelled SIP 2) constructed with non-rigid sealants. Note the “humpback” shape of the backbone curve. Based on the testing, it is believed that the humpback shape is related to the non-rigid sealant adding strength and stiffness. The nature of the sealant resulted in a non-catastrophic loss of load. When the sealant bond reached the ultimate shear strength (or shear strain), the remaining resistance was from the mechanical fasteners.

By inspection, it can be noted that SIP 2 meets the backbone curve criteria. Although not shown, SIP 2 also meets the normalized cumulative energy criterion. Given that the peak load is significantly higher than the control, which leads to a significantly higher factor of safety, the inherent over-strength of the SIP 2 assembly is higher than the conventional wall system. This inherent over-strength could be important if the lateral force resistant system is detailed for ductile failures. However, it is possible that the designed collector will not be able to transfer the required load into the ductile element. In terms of deflection amplification, the case is not as clear. Although the peak load is achieved at a relatively small drift (less than 1% drift), the ultimate displacement is significantly higher than the displacement at the peak load. The current literature is not clear on how the deflection amplification factor would be estimated for a system that exhibits a humpback shape.

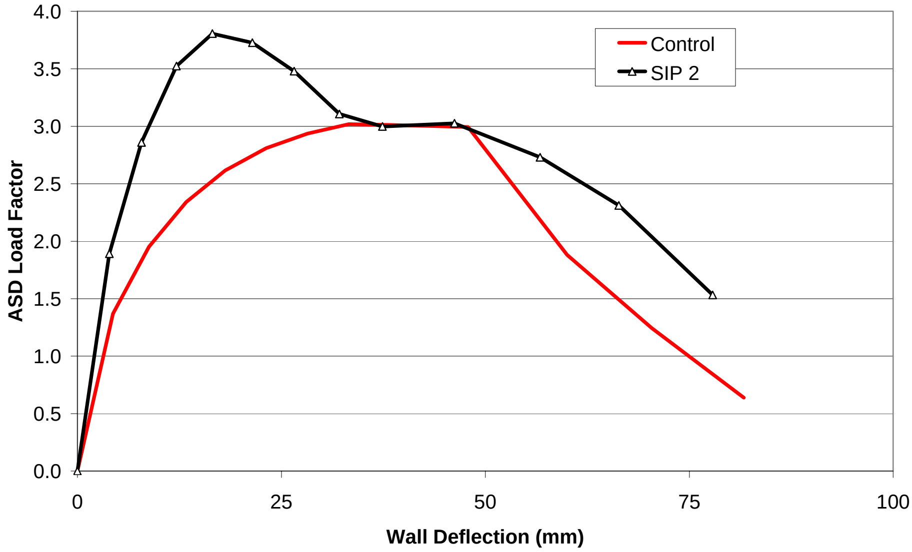

Figure 5. Backbone curve of 2.4-m tall assembly with non-rigid sealants that passes the proposed criteria

4. Conclusions

The aforementioned comparison is based on matched wall tests. The basis for the evaluation is light framed wood walls sheathed with wood structural panels, which are a listed system in terms of seismic design coefficients. Based on cyclic testing of the known system, a normalization technique is used such that data from conventional walls is compared to data collected on SIP assembles. There are four criteria that are examined:

1. Ultimate Load
2. Stiffness
3. Deflection at allowable story drift, and
4. Normalized cumulative energy dissipation

If the SIP systems demonstrate equivalence to the light framed systems based on the above criteria, it can be considered that the SIP systems have equivalent seismic design coefficients, as given in the 2003 IBC (ICC), for light framed walls sheathed with wood structural panels. Based on limited testing of SIP assemblies with sealants, the assemblies can meet the aforementioned criteria. It should be noted that since the performance of SIP systems is sensitive to fastener type and sealant formulation, additional matched tests may be required with significant changes in sealant formulation and fastener type.

5. References

APA. 2004. *Regional production & market outlook for structural panels and engineered wood products 2004 - 2009*. APA Economics Report E70. APA - The Engineered Wood Association, Tacoma, WA.

BSSC. 2000. *Proposal 7-7(2000) changes to 1997 NEHRP provisions*. Building Seismic Safety Council, Washington, DC.

FEMA. 2001a. *NEHRP recommended provisions for seismic regulations for new buildings and other structures, part 1 – provisions*. FEMA 368. Federal Emergency Management Agency, Washington, DC.

FEMA. 2001b. *NEHRP recommended provisions for seismic regulations for new buildings and other structures, part 2 – commentary*. FEMA 369. Federal Emergency Management Agency, Washington, DC.

ICC ES. 2004. *Acceptance criteria for sandwich panels - AC04*. ICC Evaluation Service, Inc., Whittier, CA.

ICC. 2003. *International building code*. International Code Council. Falls Church, VA.

SEAOSC. 1997. *Standard method of cyclic (reversed) load test for shear resistance of framed walls for buildings*. Structural Engineers Association of Southern California, Whittier, CA.